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Challenges to astronomy from large satellite constellations

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Image: SpaceX

A new era in space utilization has arrived: the `megaconstellations'.

As of Nov 28 2022
3558 SpaceX Starlink satellites and 464 OneWeb satellites have been launched.
FCC and ITU filings include requests for over 400,000 satellites

Existing large, but not “mega”, LEO constellations (50-500 sats):

Strela-1M	360 in orbit, 0 working
Strela-3/Gonets	185 in orbit, 51 working
Parus	143 in orbit, 3? working
Orbcomm	58 in orbit, 31 working
Iridium	108 in orbit, 75 still working
Globalstar	85 in orbit, 31 still working
Planet Doves	311 in orbit, 179 still working
Spire Lemur	116 in orbit, 48? still working

Constellations we expected based on mid-2022 FCC and ITU filings:

Starlink Generation 2: 30,000 satellites at 328 to 614 km
OneWeb Phase 2: 47,844 satellites at 1200 km
Amazon Kuiper: 3,236 satellites at 590-630 km
Guangwang 13000 satellites at 590-1145 km
Astra V-band 13600 satellites at 380-700 km
E-Space (US/Rwanda) 337,323 satellites at 530-630 km !!
and others totalling over 430,000 satellites planned
"Megaconstellations" (well, really only myriaconstellations... nevertheless unprecedented)

OneWeb sats are smaller and higher than Starlink – V ~ 8 -- 9 or so: too faint to see with naked eye but glaringly bright by astronomical detector standards.

Following bankruptcy and reorganization last year, OneWeb has reduced its proposal to only 6372 satellites (factor 7.5 reduction)

Example constellation definitions

MODEL III-B: Starlink Constellation, Modified Gen 2 Config 1 (Aug 2021 Filing, 30000 satellites)

Layer	Element	Altitude (km)	Inclination (deg)	No of planes	Sats per plane	Total sats
A	1	340	53.0	48	110	5280
A	2	345	46.0	48	110	5280
A	3	350	38.0	48	110	5280
A	4	360	96.9	30	120	3600
B	5	525	53.0	28	120	3360
B	6	530	43.0	28	120	3360
B	7	535	33.0	28	120	3360
C	8	604	148.0	12	12	144
C	9	614	115.7	18	18	324

MODEL V: (KP1) Kuiper Constellation (2019 filing, 3236 satellites)

Layer	Element	Altitude (km)	Inclination (deg)	No of planes	Sats per plane	Total sats
A	1	630	51.9	34	34	1156
B	2	610	42.0	36	36	1296
C	3	590	33.0	28	28	784

MODEL VI: (OW2R) OneWeb Constellation (2021 revision, 6372 satellites)

Layer	Element	Altitude (km)	Inclination (deg)	No of planes	Sats per plane	Total sats
A	1	1200	87.9	36	49	1764
B	2	1200	40.0	32	72	2304
C	3	1200	55.0	32	72	2304

MODEL VII: (GW) Chinese Guangwang Constellation (2021 revision, 12992 satellites)

Layer	Element	Altitude (km)	Inclination (deg)	No of planes	Sats per plane	Total sats
A	1	590	85.0	16	30	480
A	2	600	50.0	40	50	2000
A	3	508	55.0	60	60	3600
B	4	1145	30.0	48	36	1728
B	5	1145	40.0	48	36	1728
B	6	1145	50.0	48	36	1728
B	7	1145	60.0	48	36	1728

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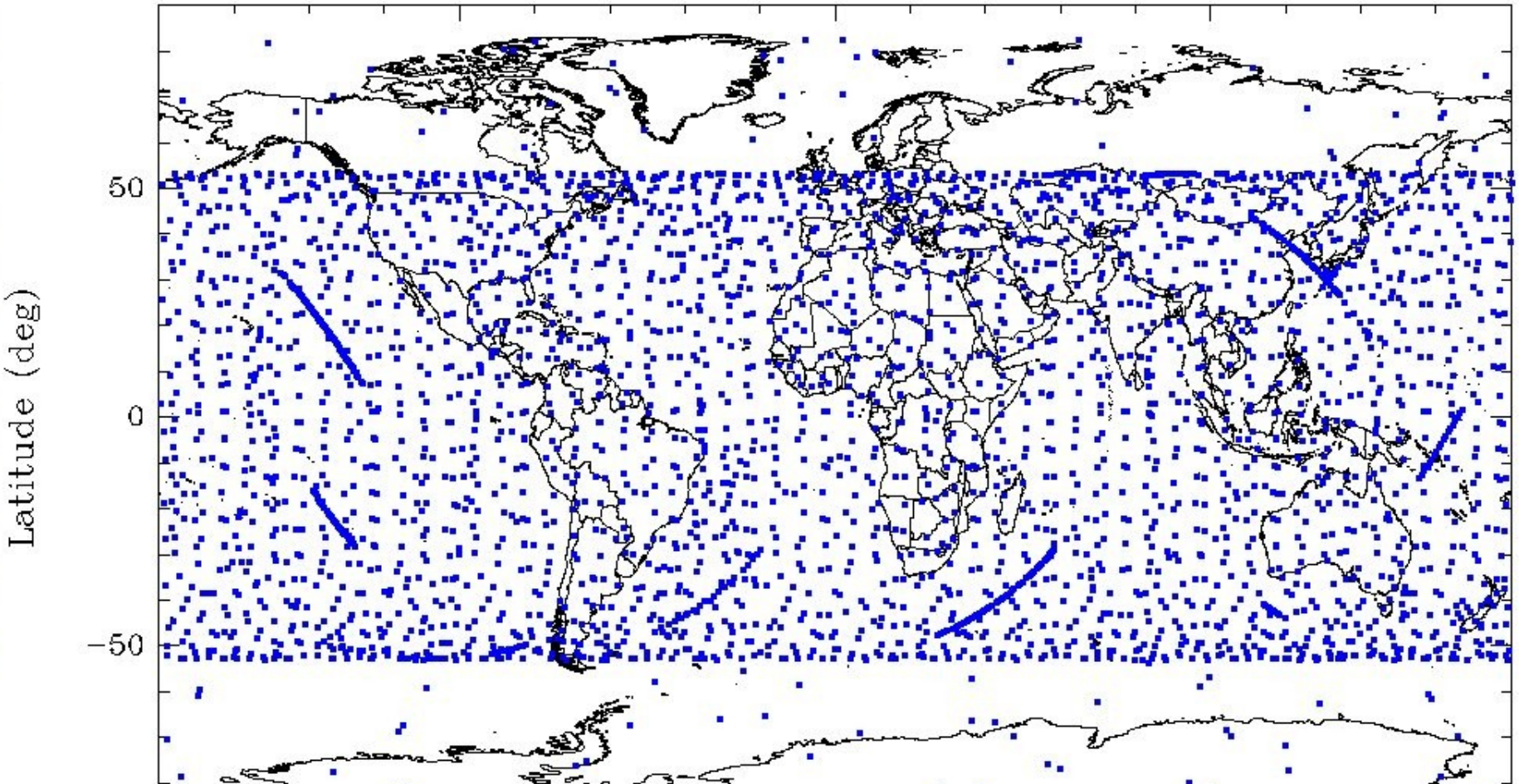
Starlinks on 2022 Oct 23 at 0h GMT:
3229 in orbit
(see https://planet4589.org/space/stats/star/stats.html)



The new entrants:

Yinhe Hangtian – Six Yinhe-2 test sats launched Mar 2022
E-Space - Three test sats launched May 2022
Boeing - Sherpa LTC2/Varuna, test sat launched Sep 2022
AST Space Mobile - BlueWalker-3, test sat launched Sep 2022
ISS Reshetnev - Skif-D, test sat launched Oct 2022

BlueWalker-3

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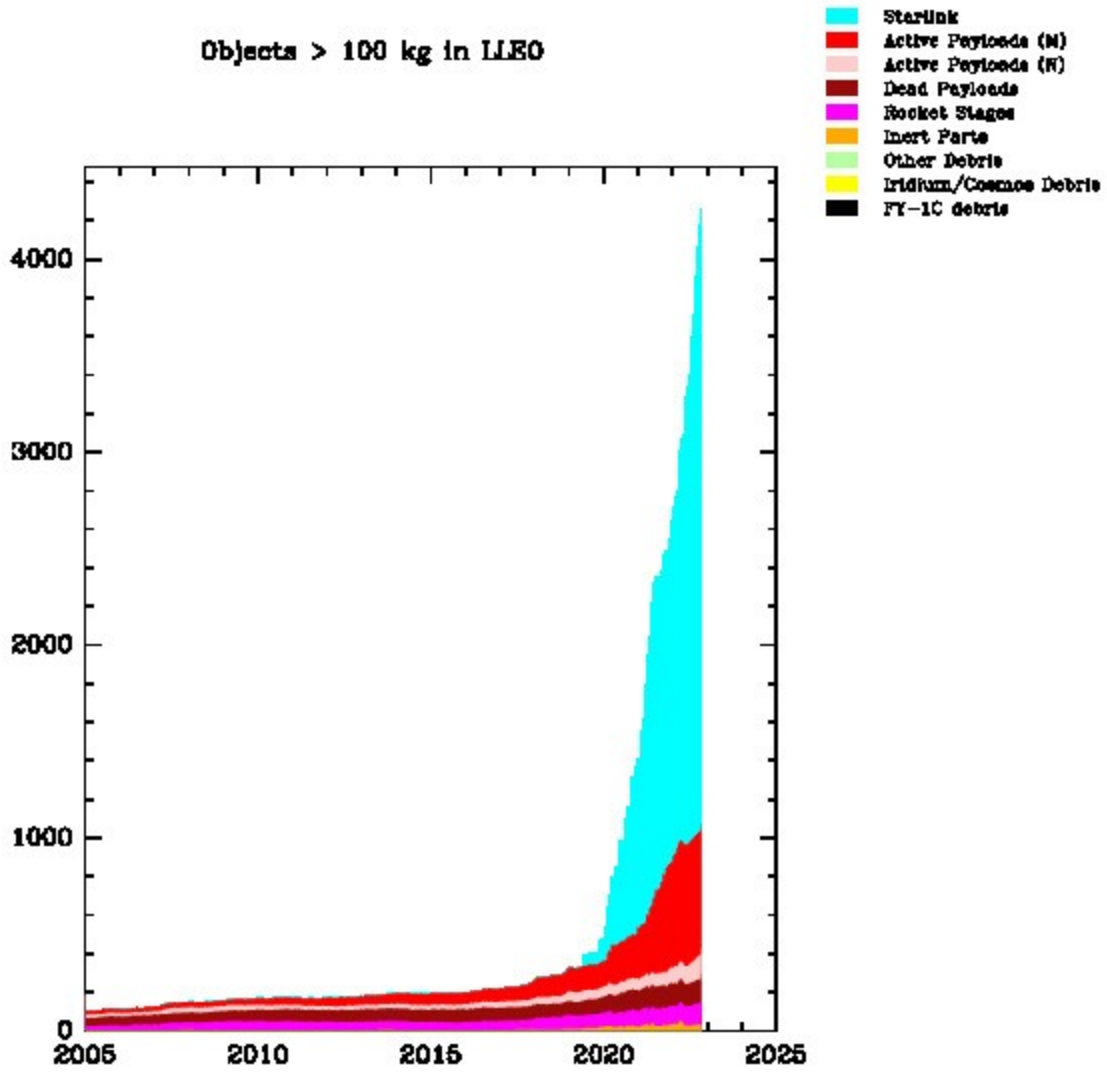

Musk: there are thousands of sats up already

BUT: mostly small debris or in high orbits

Not so many BIG and LOW: Starlink already dominates this subclass in 2022

Plot shows tracked objects below 600 km and more massive than 100 kg as of Oct 23 (Starlink in cyan)

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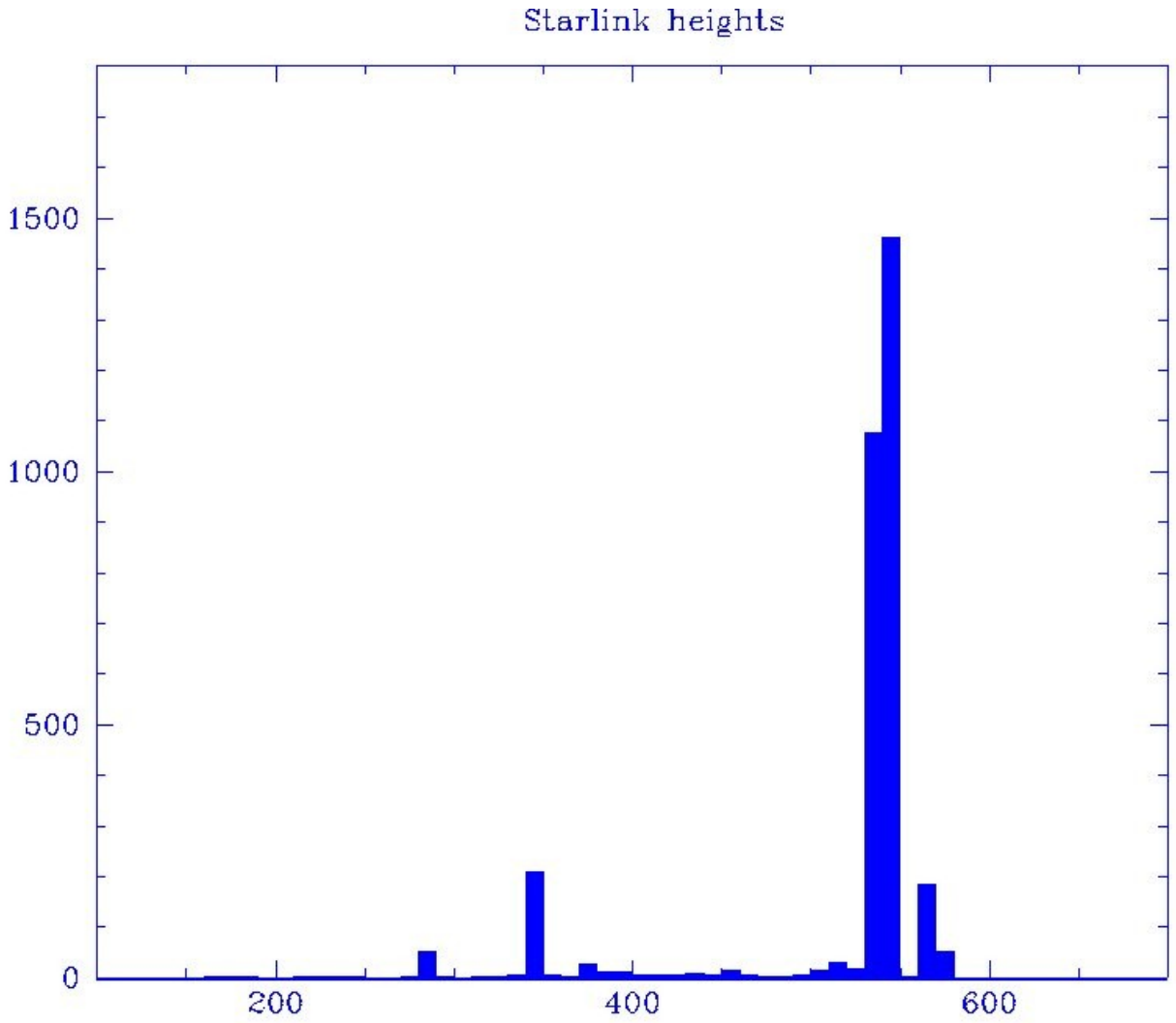
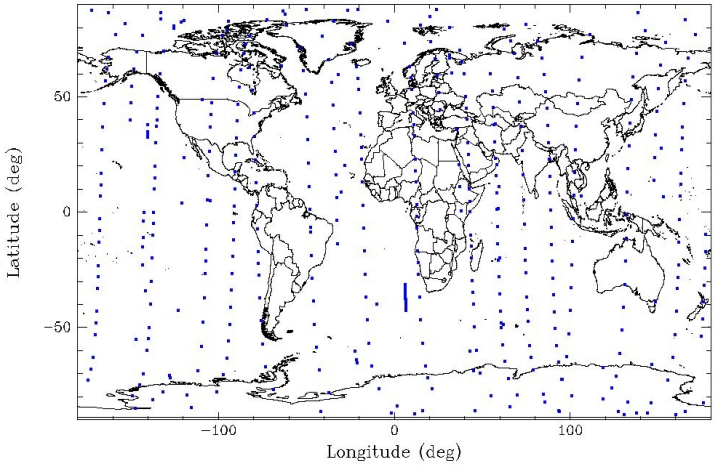
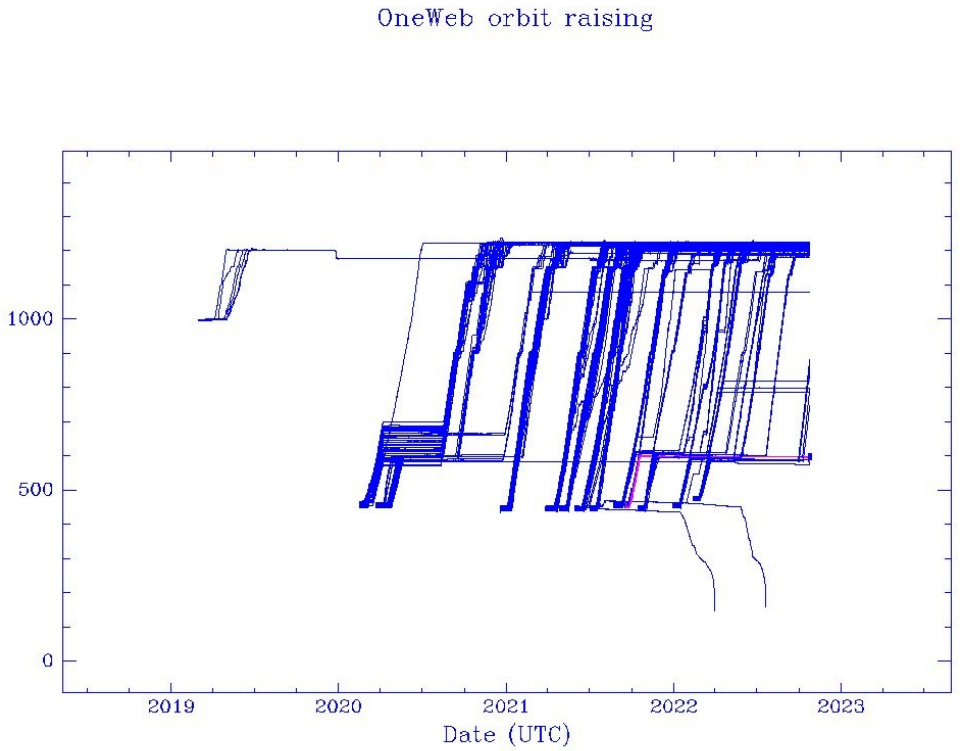


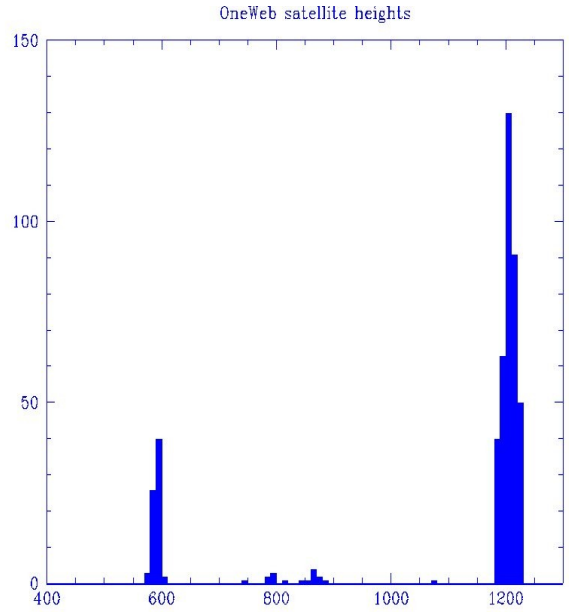
3229 in orbit

400 (12%)
below 500 km

OneWeb:







Only 2 total failures to date, plus 2 actively deorbited
High orbit -> critical that orbits are lowered at retirement

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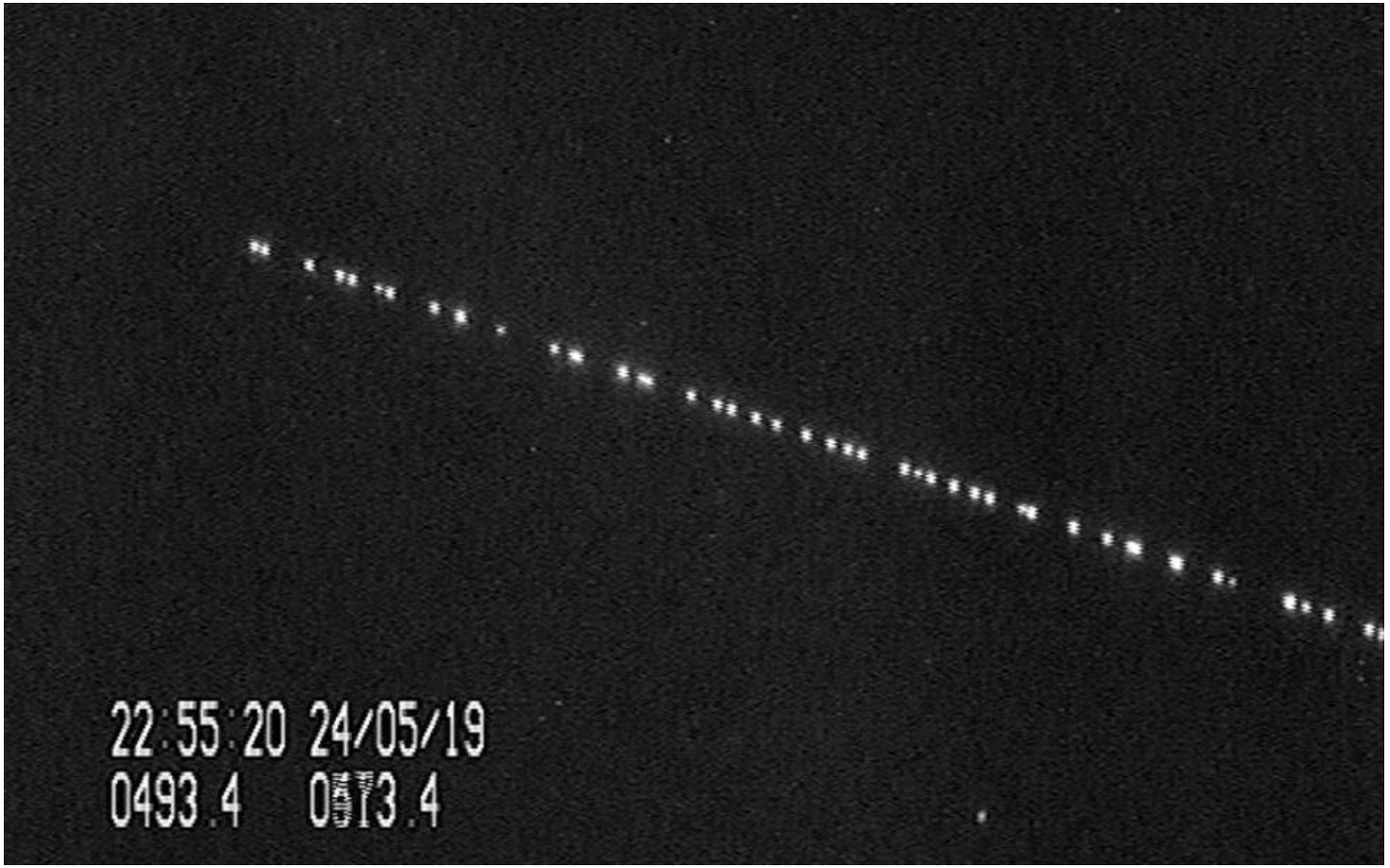
May 2019, first Starlink launch:
Astronomers see a train of satellites across the sky as bright as the familiar constellations.
What happens when there are 100,000 of these?



- Satellites became fainter once they switched to operational orientation
- Fainter still once orbit was raised to 550 km operational altitude
- Current Starlinks even fainter once visors were added
- Still naked-eye in dark skies for part of the time

BUT
- This very first observation made it clear that it is TECHNICALLY POSSIBLE to launch a bright naked eye constellation that would outnumber the visible stars

- Change the night sky for everyone? Everyone in the world, including non-spacefaring nations that may not have paid attention but have cultural connections to the night sky....

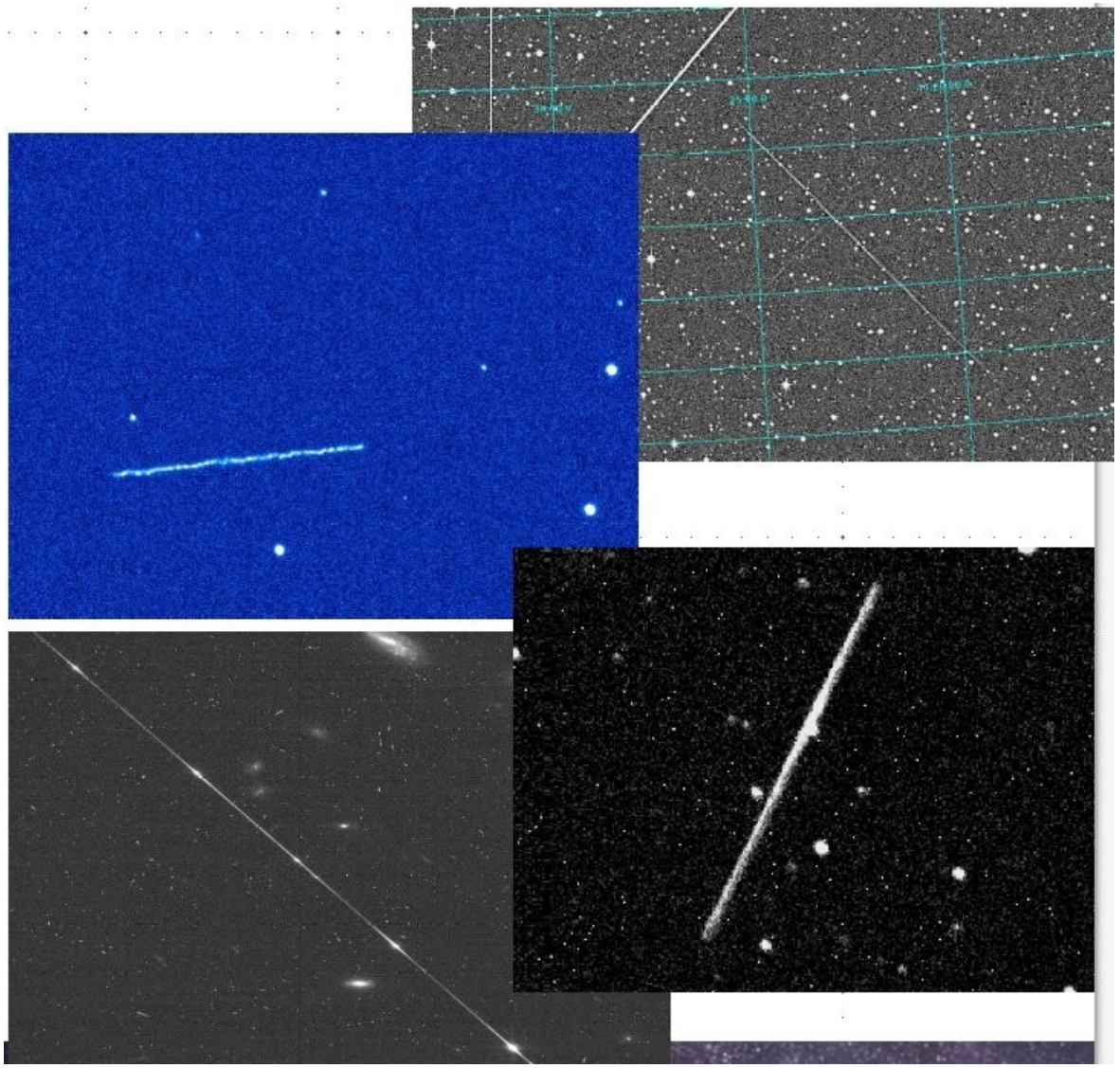
- Next generation Starlinks will be in a lower operational orbit and will not have the visors (which interfere with intersatellite laser links). Not clear yet how bright they will be.

- Nothing to stop some other country licensing a very bright LEO megaconstellation

More and more frequently our astronomical images are marred by satellite streaks

Astronomers aren't just taking pretty pictures – we do things like measure star brightness to 1% accuracy

So just cosmetically fixing the obvious streak isn't enough. The data are compromised.



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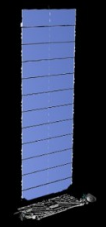
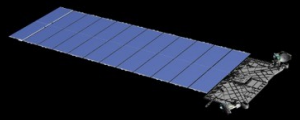
On station, brightness is driven by antennas since the satellite is in the "shark-fin" configuration during sunset and sunrise.



SHARK-FIN

During orbit raise, brightness is driven by the "open book" configuration for thrusting and drag and sunlight reflects off both the antenna and array.



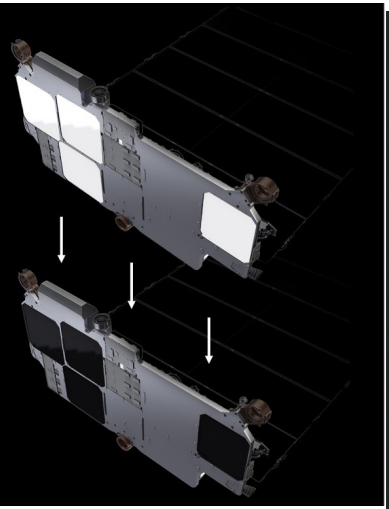
OPEN BOOK

Starlinks are:
LARGE (260 kg, ~10m)
and LOW (300-550 km)
and REFLECTIVE.
- Bright (naked-eye) objects)
- Mitigations have reduced brightness by about 1 mag

Images: SpaceX

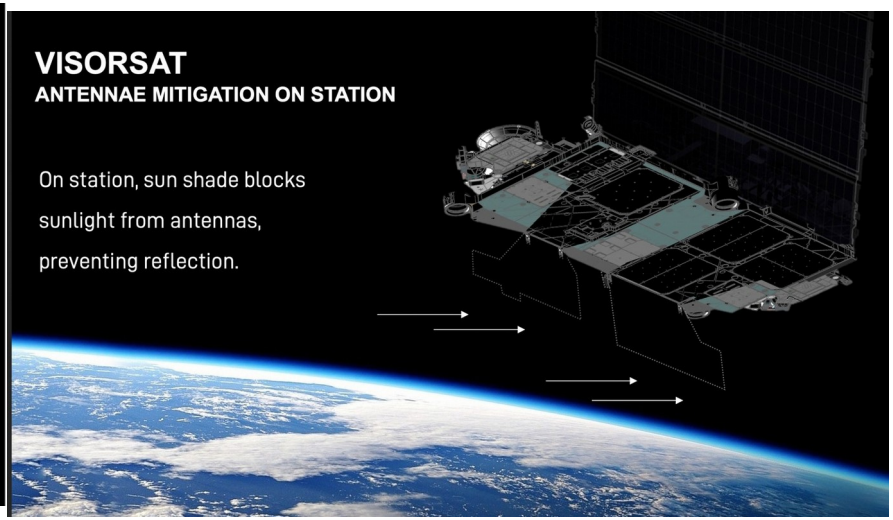
DARKSAT
ANTENNAE MITIGATION ON STATION

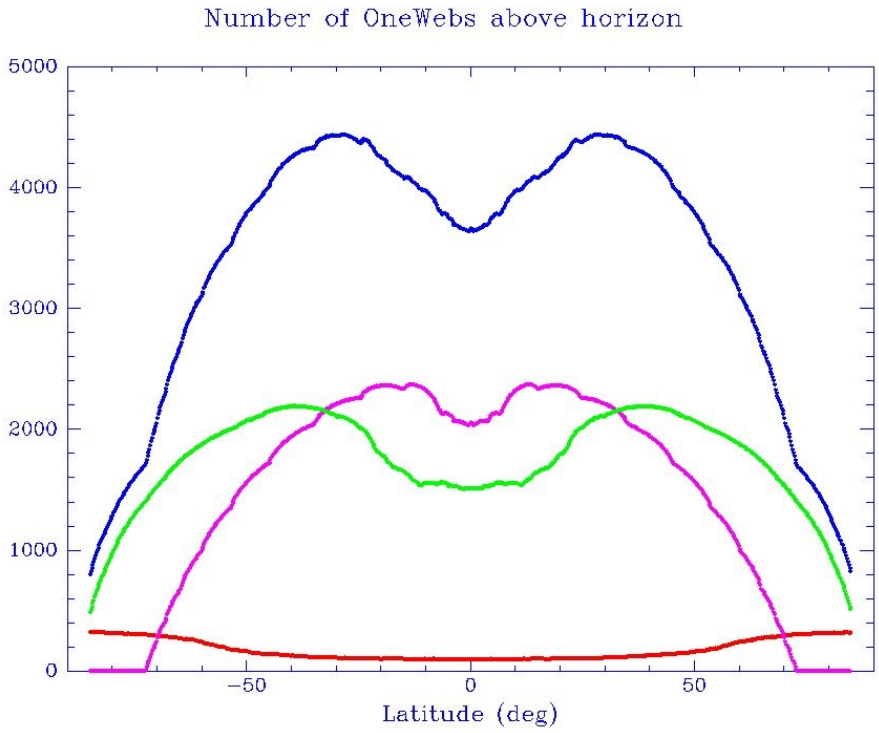
Ground-based observations of our initial test experiment proved we can significantly reduce brightness. Subsequently, we developed a higher-performance option.



VISORSAT
ANTENNAE MITIGATION ON STATION

On station, sun shade blocks sunlight from antennas, preventing reflection.

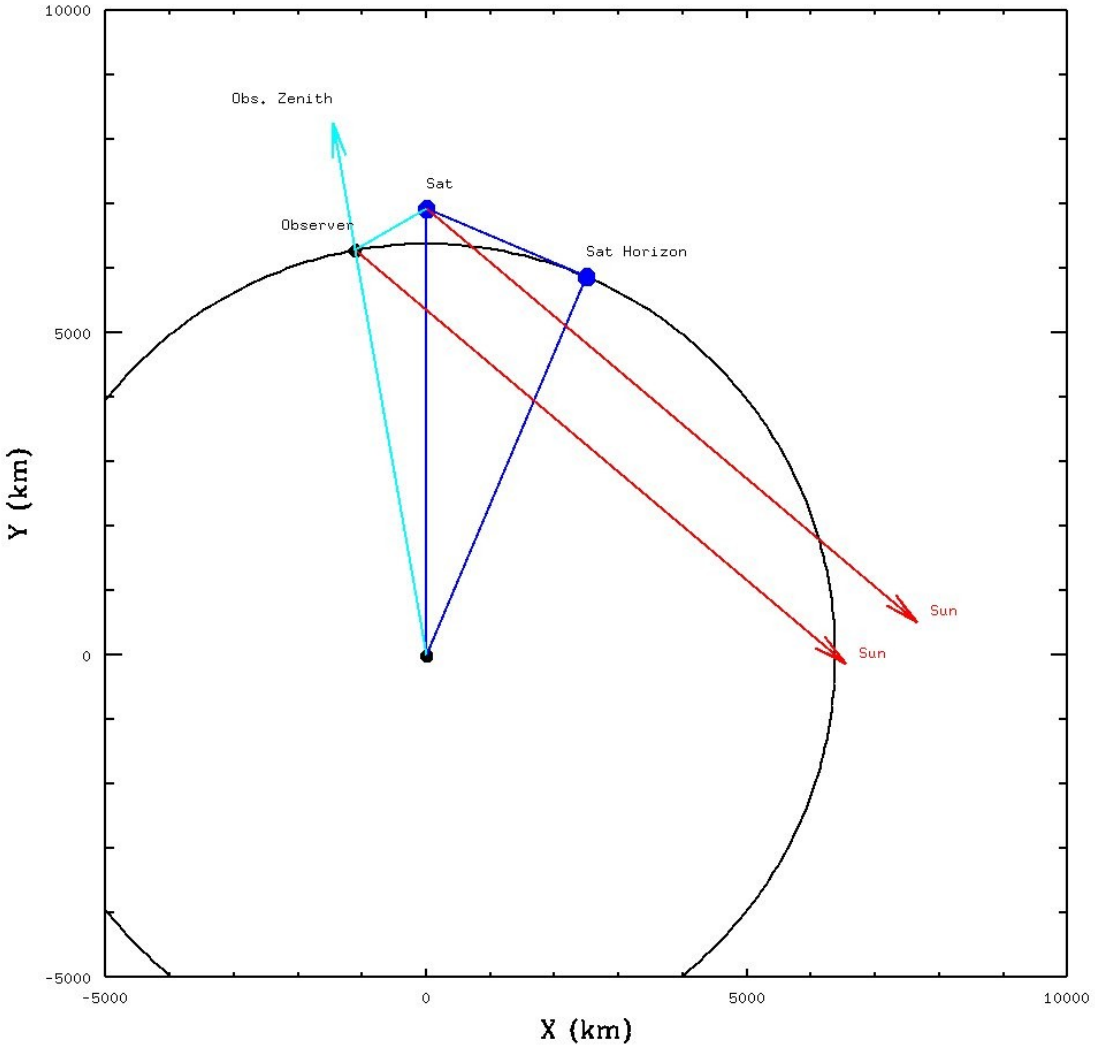




We can plot these realizations versus latitude from the point of view of an observer at those latitudes

Here, for the *original* OneWeb Phase2, I show how three shells at three different inclinations (40,55 and 88 deg) contribute to the overall number above the horizon as a function of latitude

Contribution peaks at latitudes somewhat less than the orbital inclination. Combination peaks at 30 deg – where lots of observatories are.
But not all these satellites will be illuminated all night...



How many satellites are high in the sky and illuminated when it's dark outside and astronomers are at work?

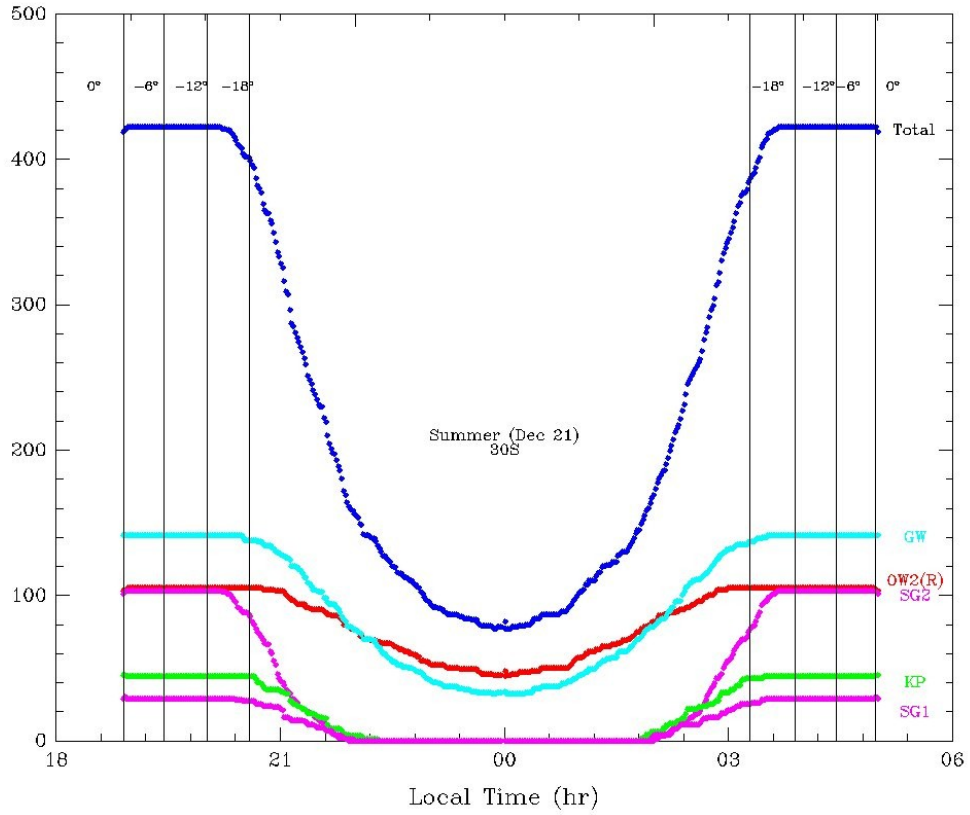
Geometry of problem involves three angles:

1) Zenith-Observer-Sat angle – **is the Sat above the horizon,** and is it above 30 deg elevation (airmass 2)?

2) Zenith-Observer-Sun angle: **is it night where the observer is?** How far below the horizon is the Sun? (e.g. "Astronomical twilight")

3) Sat Horizon-Sat-Sun angle: is it night where the satellite is? **Is the satellite illuminated?**

Number illuminated with elevation > 30°



30 deg S corresponds to Cerro Tololo, Chile and other major observatories

At summer solstice, 100 illuminated satellites high in the sky all night long

Dominated by the OneWeb constellation because its satellites are in higher orbits

At twilight, Guanwang dominates

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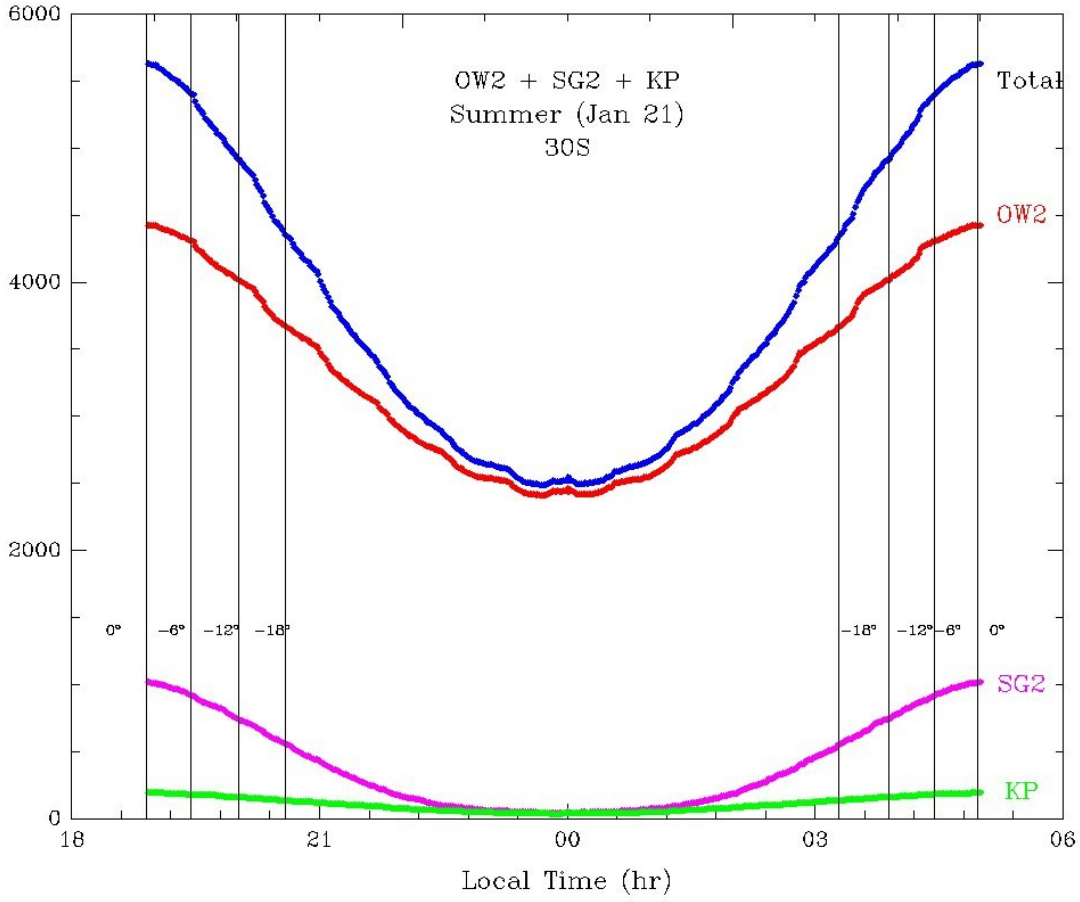
Number illuminated with elevation > 0°



Worst case: observing near horizon during twilight.

Over 5500 satellites illuminated (30S, summer)

Even without the OneWeb contrib, 500-1000 during twilight hours from Starlink Gen2

Implications:

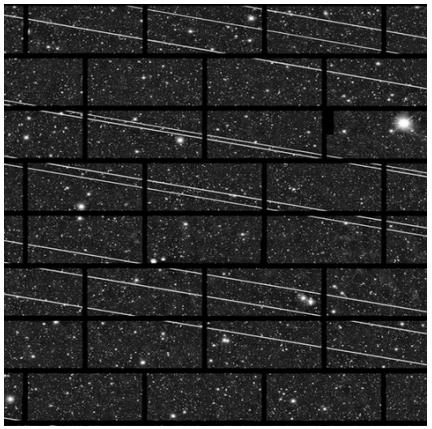
n = 500 satellites above 30 deg elevation corresponds to 0.2 sats per square degree

They are mostly OneWebs at 1200 km, angular velocity at zenith is ω = 0.35 deg/s (scales roughly as 1/height)

The expected number of satellite streaks on an astronomical image with field-of-view width D and exposure time T is

$$N = 3.7\ (n/500)\ (\omega / 0.35\ \text{deg/s})\ (T / 60\text{s})\ (D / 1\ \text{deg})$$

So for LONG EXPOSURES with a WIDE FIELD OF VIEW all images will have multiple streaks, very hard to mitigate.



Higher orbits:

- each satellite visible by more observers
- so, more of the constellation visible to each observer

- satellite illuminated by the sun longer into the night

- angular velocity lower, so surface brightness of trailed image is higher

Lower orbits:

Rubin Obs experiments show V < 7 sats can cause electronic ghosts in CCD affecting whole field

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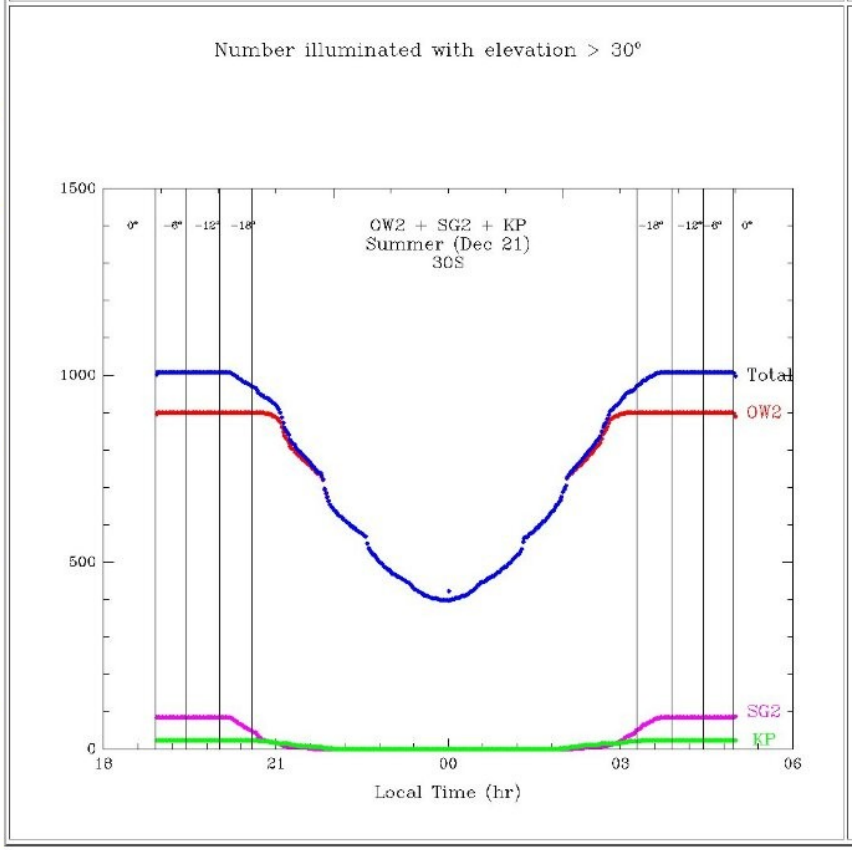
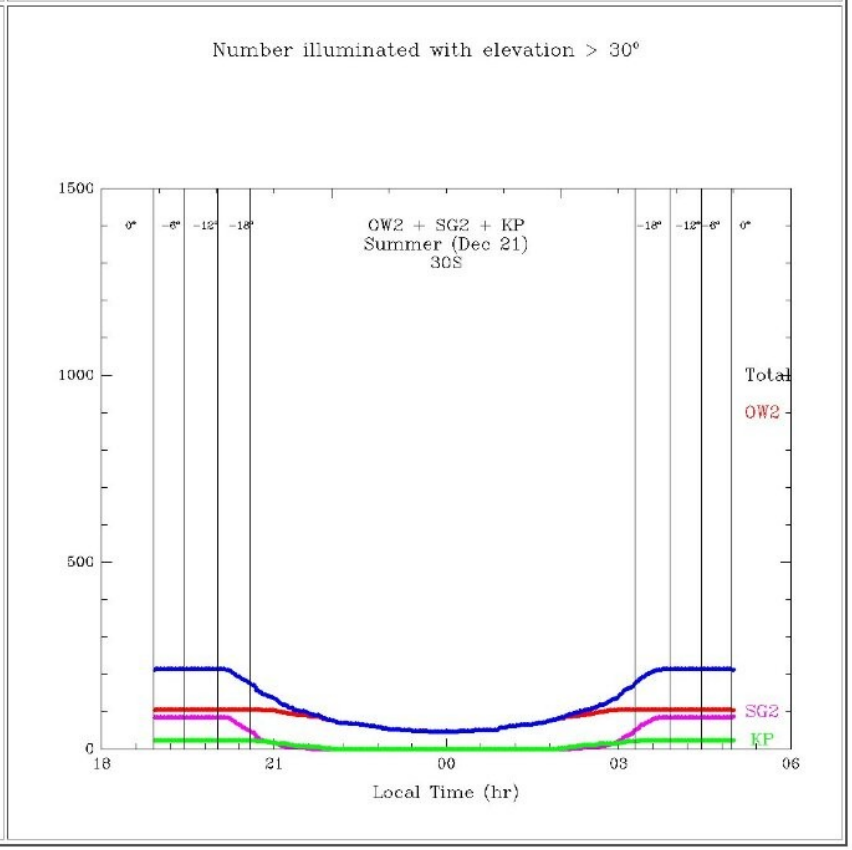
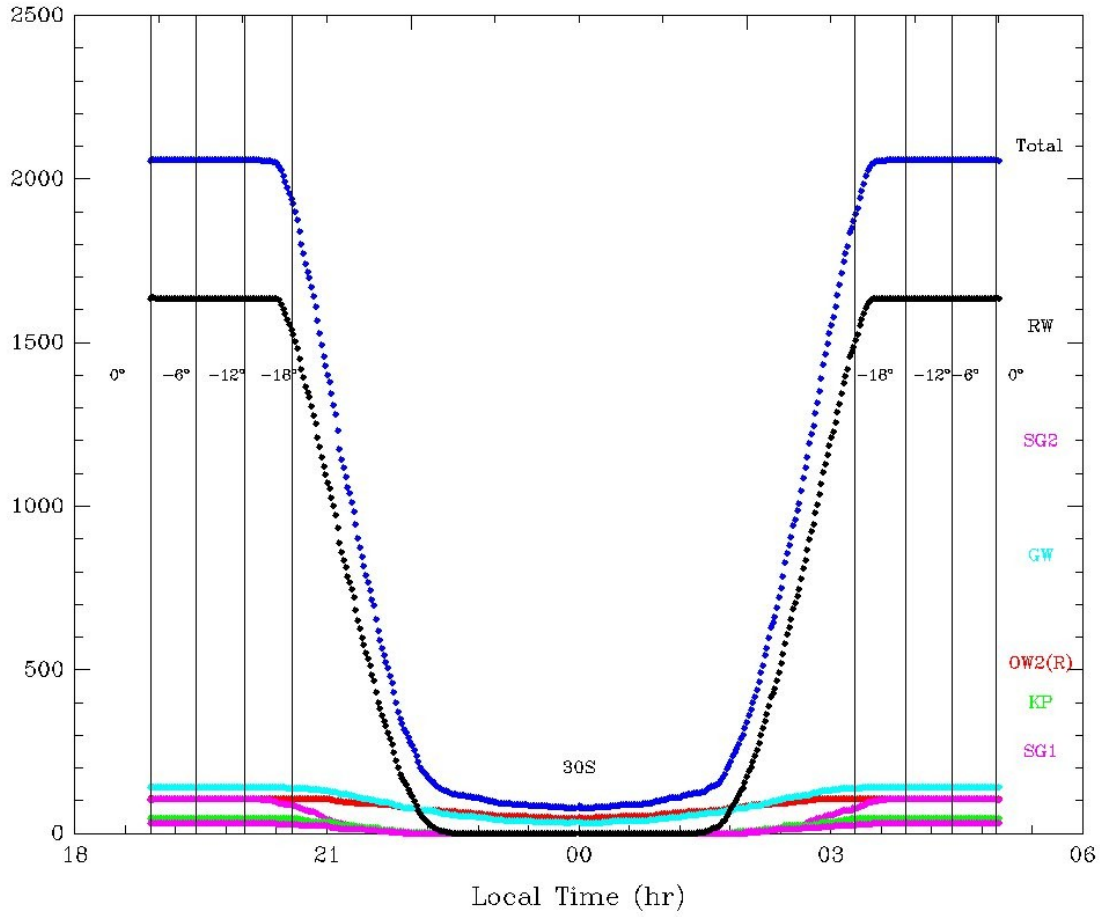
Reduction of proposed OneWeb constellation in 2021

In Jan 2021 OneWeb announced a major reduction in the number of planned satellites in their constellation. Here I show the combined OneWeb/Starlink Gen 2/Kuiper visibility plots at 30 deg South in summer, for both the old and the new plans.

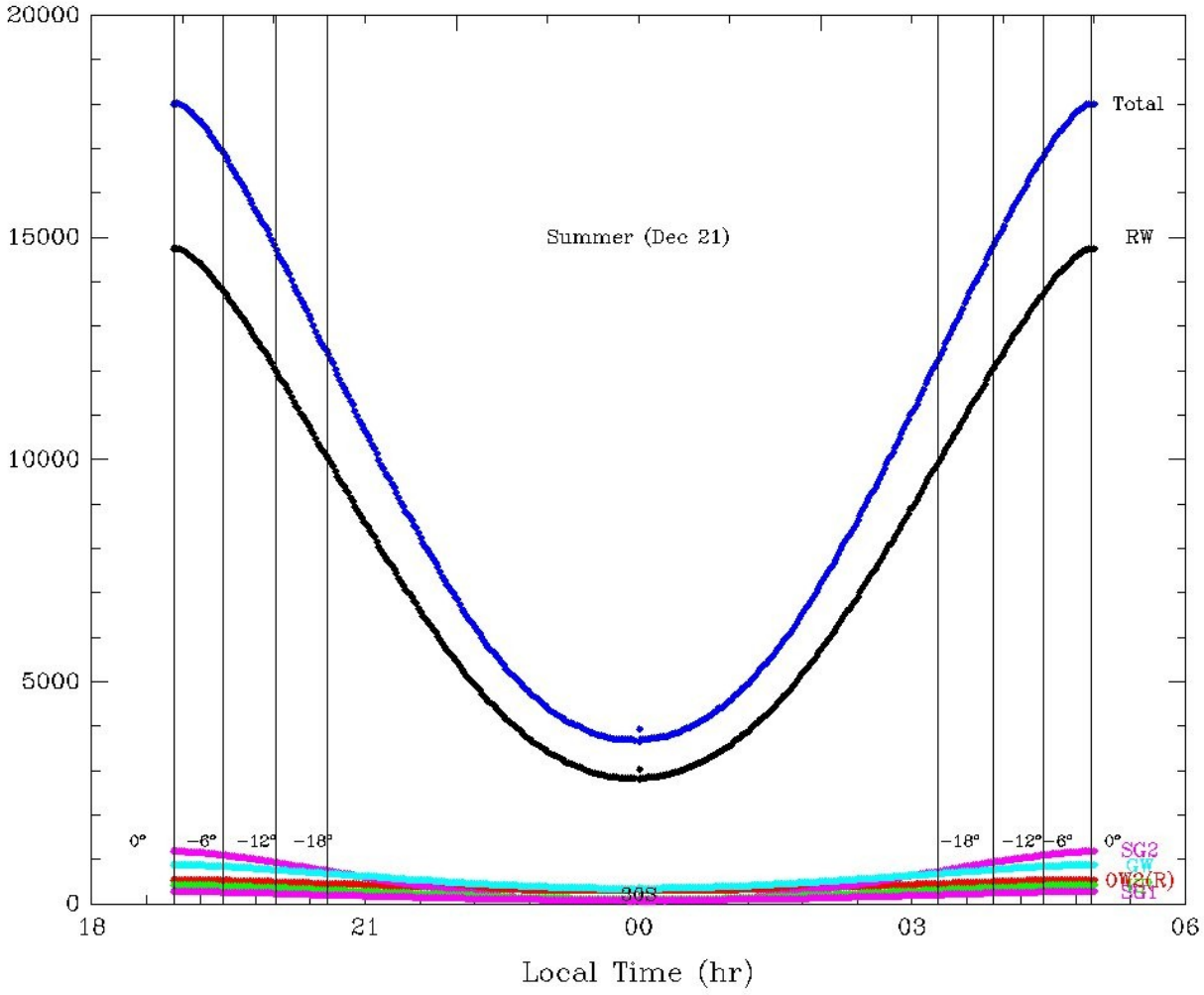
Old plan	New Plan
	



Oct 2021 ITU filing from Rwanda: 320,000 satellites proposed!!

Actually from E-Space, company led by telecom mogul Greg Wyler

Number illuminated above horizon



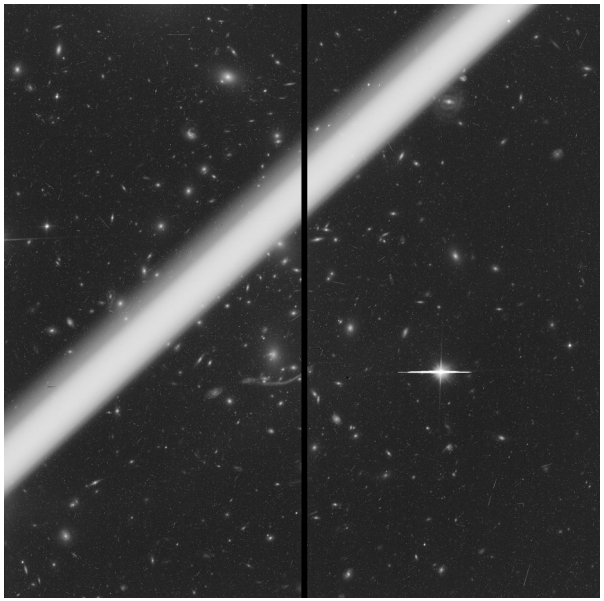
4000 sats above horizon in summer even at midnight?

What about LEO space telescopes?
OneWeb at 1200 km is above them

Hubble Space Telescope, currently at 540 km, has narrow field of view (3') but long exposures (20 min to 1 hr?). Starlinks are 10 km above it.
Orbit geometry changes angular velocity factor (but only by O(1)-O(10) or so)
BUT HST pixels are small, streak surface brightness reduced

Conclusion: Problem exists for HST but less severe
Any wide-field telescope in LEO would be in very big trouble.

Image courtesy Judy Schmidt: Chinese rocket stage passes 35 km above HST in Feb 2020, right in direction telescope was looking.



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Astronomical community response:

SATCON working group at AAS

NoirLab/AAS SATCON1 conference, July 2020: Report to AAS
NoirLab/AAS SATCON2 conference, Jul 2021: Report to be released soon

IAU/UN Dark and Quiet Skies conference,Oct 2020: report presented to UN COPUOS Apr 2021
DQS 2 – Oct 2021, report in prep for UN COPUOS

Going forward

- Work with satellite companies on mitigation
- Continue public pressure
- Work with UN COPUOS on protecting the sky?

The night sky as part of humanity's heritage and environment

Conclusion on astronomy impacts:

The megaconstellations will be a significant change to the LEO environment and to the night sky

Impact on astronomy depends sensitively on constellation architecture

Lower (500 km and less) orbit satellites may be naked eye objects but this can perhaps be mitigated with changes to satellite design. They are illuminated near horizon so are a threat to some (NEO search?) but not most astronomical observations

Higher (~1000 km) constellation shells will be illuminated all night long in summer and will be visible over a wider area – and so, although not naked-eye, will be a threat to professional astronomy.

Policy and legal issues:

Is the night sky part of "the environment", subject to environmental regulations?

Is astronomy a "space activity" under the Outer Space Treaty and does the "due regard" clause apply?

Can we get the UN to say that the night sky is part of humanity's heritage and should be protected?

Current US licensing requires companies to do a debris assessment. Can we require them to do a brightness assessment as well?

Living with big constellations: can we regulate along the lines of 'no more than X satellites above brightness Y' ?